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Model of extended emission of short Gamma-ray Bursts

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ABSTRACT
Until now the existence of extended emission is an intriguing property of short bursts. It is not clear what is the nature of the extended emission. It might be a rising x-ray afterglow, or it could be a manifestation of the prolonged activity of a central engine. We consider short duration gamma-ray bursts, emphasizing the common properties of short bursts and short burst with extended emission. Assuming that the extended emission with broad dynamic range is a common property of short bursts, we propose a two jet model which can describe both short main episode of hard spectra emission, specific for short bursts, and softer spectra extended emission by different off axis position of observer. The toy model involves a short duration jet powered by heating due to $\nu\tilde{\nu}$ annihilation and long-lived Blandford-Znajek jet with significantly narrow opening angle. Our proposed model is a plausible mechanism for short duration burst energization, and can explain both short burst with and without extended emission within a single class of progenitor.

Key words: Gamma-ray burst: general; accretion discs

1 INTRODUCTION

It is commonly accepted that Gamma-Ray Bursts (GRB) consist of two populations - long and short duration bursts. The presence of separate short Gamma-Ray Burst (SGRB) population was suggested in (Mazets & et al. 1981), and confirmed by the BATSE experiment (Kouveliotou & et al. 1993). The nature of SGRB can be merging of compact companions in close binary systems such as neutron stars (NS) or NS Black-Hole (BH) (Blinnikov et al. 1984; Paczynski 1986). Short GRBs have several distinct phenomenological properties which we briefly discuss.

SGRBs populate the short mode of a bi-modal duration distribution. The duration parameter, T_{90}, is defined as continuous interval comprising the 90% of GRB emission in gamma-ray domain (Koshut & et al. 1996). It is also accepted that the $T_{90} < 2$ s is a good dividing line for short and long bursts for mid-energy-range ($30 - 300$ keV) experiments e.g. (Kouveliotou & et al. 1993). Later on a more complex criterion has been suggested in order to distinguish phenomenologically short and long GRB (Donaghy & et al. 2006; Zhang & et al. 2009).

SGRBs have a harder spectrum than long bursts (Kouveliotou & et al. 1993), and there is no spectral lag in their light curves in comparison with long bursts, where light curves of the same GRB in soft channel lag the light curve in harder channels (Norris et al. 2000).

In a new era of rapidly slewing robotic telescopes, the optical afterglows of SGRBs has been detected, and in some cases it is possible to determine a redshift, z, of some SGRB sources. It turn out that most SGRBs have $z < 1$ and equivalent isotropic energy E_{iso} in the range 10^{48} to 10^{51} ergs (Gehrels et al. 2009).

Finally, until now there has been no cases of a supernova signature detected, either spectroscopically, or photometrically.

One of most intriguing properties of SGRBs is that they exhibit extended emission. Prompt gamma-ray emission of SGRB consists of a short main episode, sometimes resolved into substructure of short pulses, which we call the Initial Pulse Complex (IPC). The duration, T_{90}, of the IPC of the short burst is usually less than ~ 2 s. However, in the sum of light curves of many short bursts, aligned relative to the main peak of the IPC, significant extended emission (EE) has been observed up to ~ 100 s in different experiments and energy bands, in particular the BATSE $25 - 110$ keV (Lazzati et al. 2001) and $50 - 300$ keV (Connaughton 2002) (see Figure 1) (Connaughton 2002), Beppo-Sax $40 - 700$ keV (Montanari et al. 2005), Konus $20 - 750$ keV (Frederiks & et al. 2004), and SPI-ACS > 80 keV (Minaev et al. 2009, 2010). Indeed, the T_{90} parameter of each short burst to be summed is less than ~ 2 s. The intensity of the EE seems to depend on the energy band being smaller with increasing

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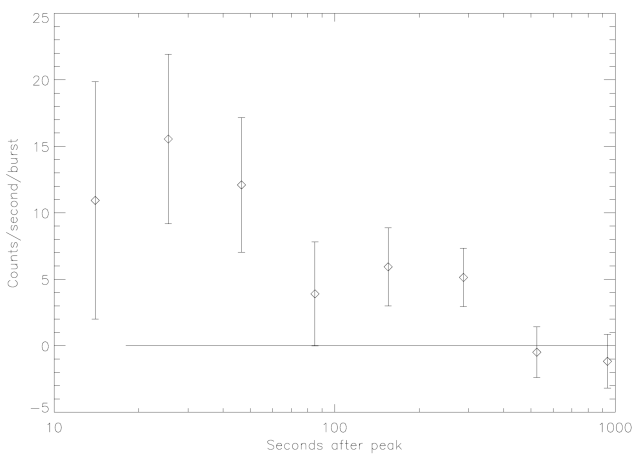

Figure 1. Light curve in 50 - 300 keV energy band for 100 short (< 1 s), summed, background subtracted, BATSE bursts after peak alignment. The time interval corresponding to a peak is not shown, adapted from (Connaughton 2002).

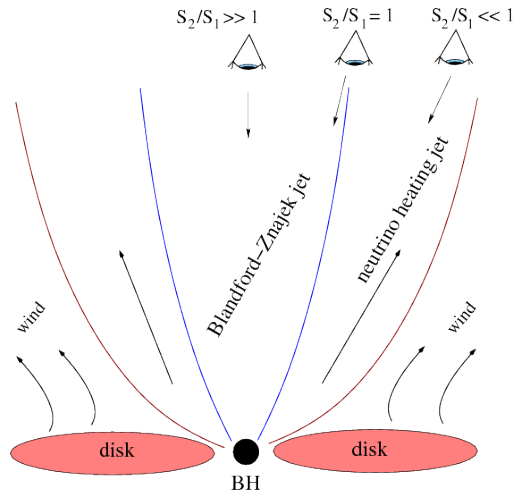

Figure 3. A scheme of a two component jet model. Observer will register different fluence of short episode of initial emission and extended emission depending on the angle of view against axis of the jets.

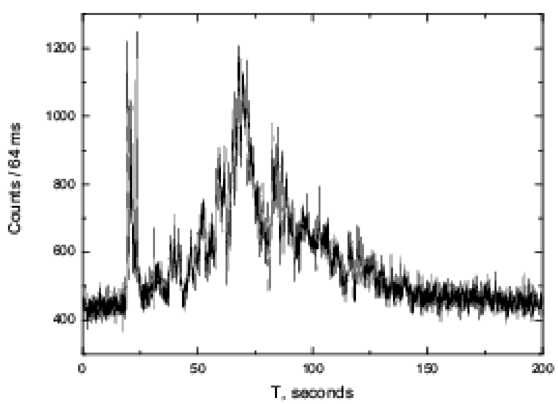

Figure 2. Light curve of GRB060614 in 15 - 150 keV energy band as recorded with BAT/Swift, time bin is 64 ms.

the energy band, and fluence ratio of the EE episode and the IPC may be less than 1/100.

The EE is softer than the IPC, however it is not clear yet if this EE is a rising X-ray afterglow or manifestation of prolonged activity of the central engine of the burst source. Also, based only on the statistical investigation of a large amount of short GRBs, one cannot say for sure that each particular burst has extended emission.

Extended emission has actually been observed in individual light curves of some SGRB, confirmed with KONUS (Frederiks & et al. 2004), HETE-2 (Villasenor & et al. 2005), Swift (Barthelmy & et al. 2005), BATSE (Norris & Bonnell 2006), SPI-ACS/INTEGRAL (Minaev et al. 2010). Despite the T_{90} of some bursts being less than 2 seconds, those the EE are significantly detected after re-binning original light curve onto larger time scales. In all cases above, the EE has a peak flux and fluence much smaller, than analogues parameters of the IPC.

Among the long duration BATSE bursts, several GRBs with phenomenological features resembling short bursts were found, where IPC does not possess any spectral lag and there is a tail of softer emission with durations up to 100 s (Norris & Bonnell 2006). The visually estimated amount of this burst type is about 2% of the total amount of BATSE bursts. While the peak flux of the EE is still 10-30 times less than the peak flux of the IPC, the fluence of the EE is compatible with the fluence of the IPC.

Finally, the ultimate example of an apparently long burst ($T_{90} = 102$ s, see Figure 2) with all signatures of short bursts is Swift GRB 060614 (Gehrels & et al. 2006). In addition to the absence of spectral lag in the whole light curve (both in the IPC and the EE), the host galaxy was identified at z=0.125 and deep and temporally dense follow-up optical observation did not reveal signature of a supernova, placing the brightness of any possible supernova associated with GRB 060614 unreasonably faint $M_R > -13.6$ (Fynbo & et al. 2006; Gal-Yam & et al. 2006; Della Valle et al. 2006).

It is evident that the intense EE of SGRBs was observed in a few cases, whilst the less intense EE can be observed more frequently. Using BAT/Swift, which is more sensitive to the EE of short bursts, it was shown that among Swift SGRBs that $\sim 25\%$ of short bursts have EE (Norris et al. 2011). It is also evident that weak EE are observed in the *majority* of short bursts because sum of the light curves possess EE, whilst in individual light curves, the EE is below the detection level.

Thus one could suggest that for short duration bursts (or the phenomenon responsible for what we mean as short duration bursts) have a distinctive feature, such as extended emission with very broad dynamic range of flux and fluence of the EE. We suggest that EE is an inherent property of short bursts, and an observable property of the EE can be explained by the different angular position of the observer with respect to the axis of the coaxial jets (see Figure 3).

2 THE MODEL

In our model, we assume the merging of two NSs or a NS+BH system which can lead to formation of a fast-rotating black-hole ($a = J/M_{BH}^2$, where a is dimensionless BH spin parameter). Simulations of the merging of the BH+BH or BH+NS give values of final a as $0.3 \le a \le 0.65$ (Baker et al. 2008; Ruffert & Janka 2010), and in our calculations, we will assume $a = 0.5$, the formation of relatively massive $M_d \sim 0.001 - 0.2 M_\odot$, and compact $R_d \sim 10^7$ cm accretion disk (Lee & Ramirez-Ruiz 2007). Such a disk is optically thick and photon cooling is not efficient and in the case of ineffective neutrino cooling, such a disk also becomes geometrically thick.

To explain the extended emission of SGRBs, we suggest a two-component model with neutrino heating (Woosley 1993) and an electromagnetic Blandford-Znajek (BZ) mechanism (Blandford & Znajek 1977; Lee et al. 2000; Mizuno et al. 2004; Barkov & Komissarov 2008; Rezzolla et al. 2011). A short main episode (IPC) of SGRB is the result of a fast accretion period (Popham et al. 1999), which launches a neutrino powered jet. After a few seconds, neutrino heating becomes ineffective, however, the lower accretion rate can keep the central engine active for a longer time due to the BZ mechanism (Barkov & Komissarov 2010). The duration of the BZ powered jet will depend on the mass in accretion disk.

The accretion time of main mass of the compact disk with radius $R_d \sim 10^7$ cm is short $0.1-1$ s (van Putten & Ostriker 2001). Following Metzger et al. (2008), the accretion rate can be estimated as:

$$\dot{M}_d \approx f M_d / t_{visc}, \tag{1}$$

where $t_{visc} = R_d^2/\nu$ is viscosity time scale and ν is the viscosity, and the factor $f \approx 1.6$. For the viscosity we have used an α-prescription (Shakura 1972; Shakura & Sunyaev 1973), $\nu = \alpha c_s H$, where $c_s = (P/\rho)^{1/2}$ is the isothermal sound speed and H is half-thickness of the disc. The initial viscosity time scale is:

$$t_{visc,0} \approx 0.02 \alpha_{-1}^{-1} M_{0.5}^{-1/2} R_{d,7}^{3/2} \left(\frac{H}{R_d}\right)^{-2} \ \text{s}, \tag{2}$$

where $M_{0.5} = M/10^{0.5} M_\odot$ is mass of the BH, $\alpha_{-1} = \alpha/0.1$ is the standard dimensionless viscosity, $R_{d,7} = R_d/10^7$ cm is the radius of the accretion disk.

The accretion disk will be thick and radiatively inefficient for neutrino cooling if it is larger $R_d > 300 R_g$ or $t > t_{thick} \sim 2\alpha_{-1}$ s (Chen & Beloborodov 2007), where $R_g = GM_{BH}/c^2 \approx 5 \times 10^5 M_{0.5}$ cm. For the calculation of the extended emission phase, we can use such an approximation, whilst $t > t_{thick}$, the radioactively inefficient advective flux approximation is applicable. We follow the work Blandford & Begelman (1999), and assume that only a fraction $\sim (R/R_d)^p$ of available material is accreted onto the BH. The rest of the mass will be lost to an outflow, and the parameter, 'p', can vary from 0 (no wind) up to 1 (powerful wind). The self-similar solution for accretion rate was obtained by Metzger et al. (2008). This solution gives us an accretion rate:

$$\dot{M}_{in} \approx 1.6 \frac{M_{d,0}}{t_{visc,0}} \left(\frac{R_{ms}}{R_{d,0}}\right)^p \times$$

$$\left[1 + 4.8(1-C)\left(\frac{t}{t_{visc,0}}\right)\right]^{-[1+3(1+2p/3)(1-C)]/[3(1-C)]}, \tag{3}$$

and disk radius

$$r_d \approx R_{d,0} \left[1 + 4.8(1-C)\left(\frac{t}{t_{visc,0}}\right)\right]^{2/3}, \tag{4}$$

where $M_{d,0}$, $R_{d,0}$ and $t_{visc,0}$ are initial mass, radius and viscous time of the disk, and $C = 2p/2p + 1$. The R_{ms} is radius of the marginally stable orbit (MSO) (Bardeen et al. 1972).

For the accretion of a thick disk, the maximal luminosity due to BZ mechanism can be estimated following the papers (Komissarov & Barkov 2010; Barkov 2010) **where used effect of magnetic field grows and a strong large scale magnetic field formation in the vicinity of the black hole horizon (Bisnovatyi-Kogan & Ruzmaikin 1974, 1976).**

The pressure of the magnetic field can be a fraction, $1/\beta$ (where $\beta \equiv 8\pi P_g/B^2$), of the gas pressure in the disk at MSO, from MSO magnetic field accretes to the BH horizon. In such a way, the luminosity of the BZ mechanism becomes a weak function of BH spin parameter, a, (if $0.5 \le a \le 1$) and can be estimated as:

$$L_{BZ} \approx \frac{0.05}{\alpha_{-1}\beta_1} \dot{M}_{in} c^2 \approx 10^{48} \alpha_{-1}^{-1} \beta_1^{-1} \dot{M}_{in,-5} \ \text{erg s}^{-1}, \tag{5}$$

where $\beta_1 = \beta/10$.

The main source of neutrino heating is the neutrino annihilation reaction $\nu\tilde{\nu} \to e^+e^-$. The heating rate can be described by (Zalamea & Beloborodov 2010):

$$L_{\nu\tilde{\nu}} \approx 3 \times 10^{50} X^{-4.7} M_{BH,0.5}^{-3/2} \dot{M}_{in,0}^{9/4} \ \text{ergs s}^{-1}, \tag{6}$$

where $X \equiv R_{ms}/4R_g$. This formula is valid when the accretion rate is higher than $\sim 0.05 \alpha_{-1}^{5/3} M_\odot$ s^{-1} (Chen & Beloborodov 2007), this critical value of the accretion rate is a function of a. As the accretion rate becomes lower, the efficiency of neutrino heating drops dramatically and becomes negligible.

In our model, the distribution of SGRBs in the intensity of the extended emission is a selection effect of different angular position of the observer (see Figure 3) with respect to the axis of coaxial jets and a dispersion of opening angles of the neutrino and BZ jets. The neutrino powered jet has the opening angle $\theta_{\nu\tilde{\nu}} \sim 0.1$ (Aloy et al. 2005; Harikae et al. 2010) and can be significantly wider than opening angle of the jet powered by the BZ mechanism $\theta_{BZ} \sim 1/\Gamma$ (Komissarov et al. 2009).

One can estimate the ratio of jets opening angles using GRB 060614. As discussed above, this unique burst has brightest EE, i.e. peak fluxes nearly the same in the IPC and the EE (Figure 2). One can suggest that GRB 060614 was observed close to the axis of the coaxial jets. Then we can write following relation:

$$\frac{L_{BZ}}{L_{\nu\tilde{\nu}}} \left(\frac{\theta_{\nu\tilde{\nu}}}{\theta_{BZ}}\right)^2 = \frac{F_{2,max}}{F_{1,max}} \sim 1 \tag{7}$$

where $F_{1,max}$ and $F_{2,max}$ are peak fluxes of the IPC and EE episodes. Using equations (5,6), we obtain $\theta_{BZ}/\theta_{\nu\tilde{\nu}} \sim 0.1$. Otherwise, one can estimate the same parameter of $\theta_{BZ}/\theta_{\nu\tilde{\nu}}$ using fluence ratio of the IPC with duration, $t_{\nu\tilde{\nu}}$, of about 5 s and fluence $S_1 = (16.9 \pm 0.2) \times 10^{-6}$ erg cm^{-2}, and the

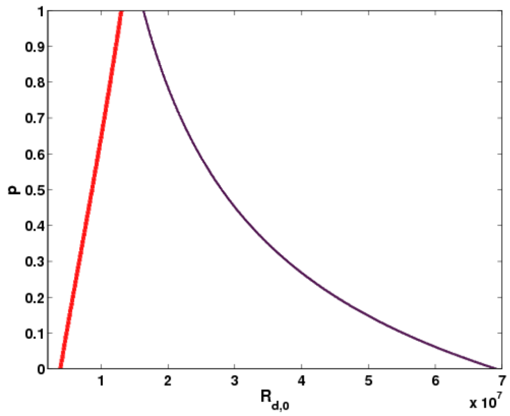

Figure 4. First episode of short emission and the extended emission is observable if initial parameters 'p' and $R_{d,0}$ is in between the lines. We take the initial mass of the accretion disk is equal to $M_{d,0} = 0.1 M_{\odot}$, $a = 0.5$ and duration of the IPC and the extended emission equals $t_{\nu\tilde{\nu}} = 1$ s, and $t_{BZ} = 100$ s. The area to the right of thick line corresponds to $L_{\rm BZ} \geq 3\times10^{-4} L_{\nu\tilde{\nu}}$. The area to the left of thin line represents the initial accretion rate $\dot{M}_{in} > 0.05 M_{\odot}$ s^{-1}

EE episode with duration t_{BZ} of about 100 s and fluence $S_2 = (3.3 \pm 0.1) \times 10^{-6}$ erg cm^{-2} (see Gehrels & et al. (2006)):

$$\frac{L_{BZ}}{L_{\nu\tilde{\nu}}} \left(\frac{\theta_{\nu\tilde{\nu}}}{\theta_{BZ}}\right)^2 \frac{t_{BZ}}{t_{\nu\tilde{\nu}}} = \frac{S_2}{S_1} \sim 5, \tag{8}$$

which leads to the comparable value of $\theta_{BZ}/\theta_{\nu\tilde{\nu}} \sim 0.1$.

Frequency detection of the EE in the individual light curves of short GRB is roughly proportional to the ratio of solid angles of the two jets. The frequency ratio can be estimated from 2% of all burst of BATSE (Norris & Bonnell 2006), and up to 25% of short bursts registered by Swift (Norris et al. 2011). Hence we have $\left(\frac{\theta_{BZ}}{\theta_{\nu\tilde{\nu}}}\right)^2 = \frac{1}{50} \div \frac{1}{4}$ and $\theta_{BZ}/\theta_{\nu\tilde{\nu}} = 0.15 \div 0.5$. One can assume that the opening angle ratio of Blandford-Znajek and neutrino powered jets is between 0.5 and 0.1. (In above estimations, we ignore any possible angular distribution of energy releases and Γ-factors of emitting particles in the jets. We also implicitly assume in eqs.(7,8) the conversion factors to the gamma-ray emission are equal in both jets.)

3 DISCUSSION

The gamma-factors of the two jets can be also different, with $\Gamma_{\nu\tilde{\nu}} \sim 500$ predicted from modelling with relativistic hydrodynamic codes for outflows (Aloy et al. 2005). The interpretation of observations with a simplified one-zone model suggests extremely high Lorentz factor of $\Gamma > 1200$ for the IPC of the short GRB 090510 (Ackermann & et al. 2010); see also Corsi et al. (2010). Nevertheless, two-zone models of GeV photon production gives a significantly lower limitation on the Lorentz factor of the jets of $\Gamma > 200-400$ (Zou et al. 2011).

Γ_{BZ} can be estimated from the value of opening angle $\theta_{BZ} \sim 1/\Gamma_{BZ}$ which is specific for BZ-jet (Komissarov et al. 2009), and ratio $\theta_{BZ}/\theta_{\nu\tilde{\nu}} < 0.5$. If $\theta_{\nu\tilde{\nu}} \sim 0.1$ we can obtain the lower limit of $\Gamma_{BZ} > 20$, which is compatible with numerical calculations of BZ-jet parameters at the time the jet is started. In the course of BZ-jet development, the Γ_{BZ} increases with time (Komissarov et al. 2009). Then the BZ jet leaves the zone of collimating wind, and the outflow can get additional acceleration due to the propagation of a rarefaction wave across the entire jet (Tchekhovskoy et al. 2010; Komissarov et al. 2010). This additional boosting will not change significantly the BZ-jet opening angle while the Γ_{BZ} could reach $100-300$.

The spectra of the IPC of SGRBs are always harder than the spectra of the extended emission and it could be explained by $\Gamma_{\nu\tilde{\nu}} > \Gamma_{BZ}$ **(see however Barraud et al. (2005))**. Another issue is an absence of the spectral lag. The spectral lag is unavoidable if the emitting particles are moving radially (Fenimore et al. 1996; Sari & Piran 1997; Norris 2002). The absence of the spectral lag in the IPC may be explained by large value of Γ (Norris & Bonnell 2006), although, it is not clear whether the lag is present in the EE. In a few cases, where the lag could be accurately measured, it is negligible within statistical errors (Norris & Bonnell 2006; Gehrels & et al. 2006). In general, more investigations of phenomenology and nature of the spectral lag are necessary.

The IPC of GRB 060614 falls far off (Gehrels & et al. 2006) the Amati relationship for long GRBs (Amati & et al. 2002; Amati 2010). However, the E_p, E_{iso} parameters of the whole burst are consistent, within 2 sigma level, with the Amati relationship for long GRBs (Mangano & et al. 2007). One would observe the GRB 060614 off-axis of the BZ-jet, such could not detect the EE, but only IPC. In this case, eventually GRB 060614 would be an outlier of the Amati relationship as we see it for other short duration bursts (Amati 2010).

Finally let us estimate physical parameters when the EE is observable. Based on the equation (8) and typical values obtained for extended emission registered for sum of the short duration bursts, i.e. fluence ratio $S_2/S_1 \sim 1$, $t_{\nu\tilde{\nu}} \sim 1$ s, $t_{BZ} \sim 100$ s and mean value of $\theta_{BZ}/\theta_{\nu\tilde{\nu}} \sim 0.2$, we can infer that the extended emission can be detected if $L_{BZ}/L_{\nu\tilde{\nu}} > 3\times10^{-4}$.

Using eq.(3) at time $t=0$, we can draw in the Figure 4 a (thin) line which shows the limit $max(\dot{M}_{in}) = 0.05 M_{\odot}$ s^{-1}. Thick line represents the limit $L_{BZ}/L_{\nu\tilde{\nu}} = 3\times10^{-4}$, and the area to the right of this line implies that there is enough energy in the BZ jet to be detected. The region between the lines provides a region in which both IPC and extended emission could be detected. Indeed in the region on the left of the thick line ($L_{BZ}/L_{\nu\tilde{\nu}} < 3\times10^{-4}$), the accretion rate is ether too slow to start BZ jet or to provide enough energy in the EE.

On the other hand, in the region to the right of thin line, the initial short period of a fast accretion rate providing a neutrino powered jet is absent. However, the accretion rate can be sufficient to start the BZ jet. Therefore one can expect the existence of rare type of long duration bursts which look like only the extended emission of such bursts as GRB 060614. The observable features of the burst are the absence of a supernova, negligible spectral lag, and a possible precursor corresponding to a failed neutrino jet. It is difficult to estimate a frequency of the occurrence of such

bursts as it will depend on the initial accretion rate distribution. However, one can remember that $\sim 10\%$ of long BATSE bursts (Hakkila & et al. 2007) actually possess zero spectral lag (see also (Norris 2002)). Indeed, some of them are short bursts with observable extended emission, as found by (Norris & Bonnell 2006), whilst some of them could be only BZ powered bursts. Recent spectral lag investigation of naturally long burst of the BAT/Swift experiment gives the same $\sim 10\%$ of burst which have negligible lag within statistical error (Ukwatta et al. 2010).

The main source of the magnetic field which is necessary to start the BZ jet can be a seed magnetic field of the merging companions. The variability of magnetic flux can be a manifestation of a magnetic dynamo in the accretion disk and the accretion of magnetic flux onto the BH (Barkov & Baushev 2011; Rezzolla et al. 2011). The accretion of magnetic flux with different polarity leads to the variability of magnetic flux on the BH horizon and thus a variability of BZ luminosity as well.

The magnetic field generated due to a dynamo can have a pressure, which can be comparable with the pressure of matter (Bisnovatyi-Kogan & Lovelace 2007; Rothstein & Lovelace 2008; Igumenshchev 2008; Lovelace et al. 2009). The pressure of the gas in the disk is a function of its thickness, $P \propto (H/R)^2$, and hence $B \propto (H/R)$, whilst the energy release will be $L_{BZ} \propto B^2 \propto (H/R)^2$. On the time scale of $t < t_{thick}$, the magnetic dynamo can generate significantly weaker fields than in the thick disk and luminosity of BZ is suppressed. In the time scale of $t > t_{thick}$ which may be of few seconds the disk becomes thicker, the magnetic dynamo becomes more efficient and provides an increased BZ-jet luminosity. The increase of the luminosity may explain the hiatus between the IPC and the extended emission observed in some short burst with EE (Norris & Bonnell 2006; Gehrels & et al. 2006).

Finally, the same mechanism involving two jets can be responsible not only for GRB based on NS-NS or NS-BH merging. Indeed the merging of BH or NS and white dwarf (Fryer et al. 1999) or BH and a core of Wolf-Rayet star (Fryer & Woosley 1998) can rise a long duration burst and exhibit a long X-ray afterglow (Barkov & Komissarov 2010) with appropriate time scaling of the main episode powered by a neutrino jet and extended emission, powered by BZ jet. The time scaling parameter will be dependent on the initial linear size (specific angular momentum) of the accretion disk, and in the case of a BH and white dwarf merging, may be ~ 10.

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